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   THE SECRETARY OF STATE FOR DEFENCE
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   If the applicant is a corporate body, give the country/state of its incorporation
   United Kingdom 5451000 2

4. Title of the invention
   "A photonic crystal fibre and a method for its production"

5. Name of your agent *(if you have one)*
   ABEL & IMRAY

   "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*
   20 Red Lion Street,
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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Number of earlier application	Date of filing *(day / month / year)*

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Description	11
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11. I/We request the grant of a patent on the basis of this application.

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ABEL & IMRAY 1st April 1999

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DUPLICATE

4905GB

The Secretary of State
for Defence

A photonic crystal fibre

and a method for its production.

Abel & Imray,
Chartered Patent Attorneys,
20 Red Lion Street,
London.
WC1R 4PQ

DUPLICATE

A photonic crystal fibre and a method for its production.

This invention relates to a photonic crystal fibre, to a method of making a photonic crystal fibre and to a method of transmitting light along a photonic crystal fibre.

Optical fibres are used for transmitting light from one place to another. Normally, optical fibres are made of more than one material. A first material is used to form a central light-carrying part of the fibre known as the core, while a second material surrounds the first material and forms a part of the fibre known as the cladding. Light can become trapped within the core by total internal reflection at the core/cladding interface. Conventional and commercial low-loss optical fibres typically have that structure; however, one limitation of the waveguiding mechanism (which we refer to as "index guiding") is that the refractive index of the material forming the core must be higher than that of the material forming the cladding, in order to achieve total internal reflection. Even if the cladding is air (with a refractive index of approximately unity) the core material must still be a solid material for the fibre to be useful. In practice, using air as the cladding material is normally not advisable, because it does not offer sufficient mechanical or optical protection of the waveguiding core. Thus, conventional optical fibres consist of a solid or liquid core material surrounded by a solid cladding.

An optical fibre waveguide having a significantly different structure from that of conventional optical fibres has been demonstrated, in which a single microstructured material is used to form the fibre core

and cladding. The introduction of morphological microstructure into the fibre - typically in the form of an array of small holes which run down the length of the fibre - alters the local optical properties of the fibre, making it possible to design and fabricate intricate waveguiding structures with most unusual properties. Such a fibre is an example of a photonic crystal fibre.

In one type of photonic crystal fibre, a fibre with a periodic array of air holes in its cross-section and with a single missing air hole in the centre (a "defect" in the crystal structure) forms a low-loss all-silica optical waveguide which remains monomode for all wavelengths within the transmission window of the silica. The waveguiding mechanism in that case is closely related to that in conventional optical fibres and is a form of total internal reflection from a material which has a lower apparent refractive index than that of pure silica.

Another type of waveguiding has also been demonstrated in a photonic crystal fibre with a periodic array of air holes. Light can become trapped in the vicinity of an extra air hole within the photonic crystal lattice (i.e. a "low-index" lattice defect), if the photonic crystal is appropriately designed to exhibit a "photonic band gap". A photonic band gap is a range of parameters - for example, a range of frequencies or wave-vectors - for which light would normally be expected to propagate in the cladding material but where there are no propagating modes due to the detail of the microstructuring. In fibres of that type that have been demonstrated to date (see, for example, J.C. Knight, J. Broeng, T.A. Birks and P. St. J. Russell, "Photonic Band Gap Guidance in Optical Fibres", Science 282 1476 (1998)), light, propagating along a fibre, is trapped in the vicinity of a

low-index defect within a fibre with a honeycomb array of air holes, but nonetheless is strongly confined to the high-index phase of the microstructured material.

A goal of researchers in the field has long been the creation of a band-gap guiding fibre in which light is trapped within an air hole itself. That goal has not, however, until now proved attainable.

According to the invention, there is provided a photonic crystal fibre comprising a region of substantially uniform, lower refractive index which is substantially surrounded by cladding which includes regions of higher refractive index and which is substantially periodic, characterised in that the region of lower refractive index has a longest transverse dimension which is longer than a single, shortest, period of the cladding, whereby light can be substantially confined in the lower index region by virtue of a photonic band gap of the cladding material and can be guided along the fibre whilst it is so confined.

We have found that use of a region of lower refractive index which is relatively large enables guidance to be achieved in the region of lower refractive index. It will be understood that the region of "lower" refractive index has a refractive index which is smaller in magnitude than the refractive index of the region of higher refractive index.

Such a fibre has advantages over other optical fibres; for example, performance may be much less limited by interaction (absorptive or non-linear) between the propagating light and material comprising the fibre. Some light may penetrate the higher-index material to a significant extent, but most light is confined to the region of lower refractive index, which might be, for

example, an air hole. Fibres according to the invention could be useful in, for example, telecommunications, environmental sensing and monitoring, high power laser transmission, long wavelength transmission and in other optical devices.

Guidance in a lower index region is possible because the photonic band gap material of the fibre cladding can behave in a manner similar in some respects to a totally reflecting, perfect metal under some circumstances but, unlike real metals, such a quasi-metal exhibits very low losses at optical frequencies. The photonic band gap material behaves like a metal when it exhibits a full 2D photonic band gap; that is, when light propagating with a particular wavevector component along the fibre and at a particular frequency sees, at all azimuthal angles, material having a band gap.

The substantially periodic cladding may have a triangular lattice structure. The triangular lattice may comprise air holes in a solid matrix.

Preferably, the regions of higher refractive index consist essentially of silica. Materials other than silica may also be used, including other silicate glasses and soft glasses of different compositions. The fraction of air in this part of the fibre needs to be relatively large to exhibit a sufficiently broad band gap. Advantageously, the fraction of air in the cladding is at least 15%, and may be more than 30%, by volume based on the volume of the cladding.

Whilst it is within the scope of the invention to provide a region of lower refractive index that is of elongate cross-sectional shape, it will generally be preferred for the region to be of generally round cross-section.

It should be understood that the fibre may include more than one region of lower refractive index.

Preferably the region of lower refractive index comprises a gas or a vacuum; the region of lower refractive index may be at atmospheric pressure (or even a higher pressure) but it may also be a low pressure region. The gas is preferably air. The substantial confinement of light to the region of lower refractive index means that the photonic crystal fibre may be capable of transmitting light at powers, and/or at wavelengths, at which it is not possible to transmit light in conventional fibres.

In an example of the invention described below the region of lower refractive index is of substantially round cross-section and has a diameter that is about 2½ times the shortest period of the cladding. Larger or smaller diameters may, however, be used. Preferably the region of lower refractive index has a longest transverse dimension at least 1.5 times longer, and preferably at least 2 times longer, than a single, shortest period of the cladding.

The actual cross-sectional dimensions of the region of lower refractive index will depend upon the wavelength(s) of light to be guided along the fibre, the period of the cladding and, in some cases, the refractive index of the region of lower refractive index. In an example of the invention described below the region of lower refractive index is of generally round cross-section and has a diameter of about 15 µm. Usually it will be preferred that the region of lower refractive index has a longest transverse dimension of at least9 µm, and preferably at least 12 µm.

A strong interaction may be possible between light in the guided mode and the fluid which may form the lower index waveguiding core; that interaction could be useful,

for example, for gas sensing and monitoring. The lower index region may comprise a material having a non-linear optical response, whereby light may be generated or modulated by non-linear processes in the lower index region.

Optical properties of the fibre can be accurately computed once the fibre size is fixed. The photonic band gap of the periodic fibre cladding can extend over a broad range of frequencies; however, in general, the mode will be guided in the lower-index region only over a relatively narrow range of frequencies. The narrowband performance of the fibre suggests that it should be useful as a spectral filtering device.

A wide variety of optical devices incorporating a photonic crystal fibre according to the invention can be envisaged. As has been described, such a device could, for example, comprise a sensor that is capable of sensing a property of the gas of which the region of lower refractive index is comprised or it could comprise a spectral filtering device. Other optical devices which could include such a fibre include, for example, an optical amplifier or a laser.

Optical fibres are widely used in the telecommunications industry. A telecommunications system could include an optical fibre according to the invention and such a telecommunications system could be included in a telecommunications network.

Also according to the invention, there is provided a method of making an optical fibre, comprising the following steps:

(a) forming a stack of canes, the stack including at least one truncated cane which defines a cavity in the stack;

(b) drawing the stack into a fibre having an elongate cavity.

Such an approach represents a modification of a fabrication process previously disclosed for photonic crystal fibres; in the known process there are no truncated canes in the stack. However, if canes are removed from the middle of such a stack and, especially if two or more canes that are adjacent to one another are removed, the resulting preform may no longer be stable and self-supporting. Even removing one cane may, however, give rise to a problem. In the method according to the invention, lengths of cane, or bundles of canes, that have the shape and size required for the final hole are embedded within the stack of canes at the opposite ends of the stack. The lengths of those embedded canes are such that they do not meet in the middle of the stack. Instead, a length (which may be approximately 15cm) intermediate the ends of the preform is left with the required large air hole, supported from either end in a stable fashion. After the (complete) preform is drawn down into a fibre (in one or more stages), only the fibre from the central part of the preform is retained.

The method according to the invention could be useful for constructing a wide variety of fibre structures, which would otherwise be difficult to manufacture. Thus the method is not restricted only to a method of making a photonic crystal fibre according to the invention.

It should be understood that the method may involve forming a stack of canes that defines more than one cavity in the stack. In that way a fibre with more than one elongate cavity may be formed.

Preferably, the cavity has a transverse dimension greater than the corresponding transverse dimension of any

of the canes. The cavity may have a transverse dimension greater than the sum of the corresponding dimensions of any two of the canes.

Preferably, the stack of canes comprises canes which are capillaries, which may form a triangular array. The capillaries may be filled with air or with a material other than air; they may be partially or completely evacuated. The cavity may have a cross-sectional area substantially equal to or greater than the cross-sectional area of a bundle of four, and more preferably a bundle of seven, of the canes.

Also according to the invention there is provided a method of transmitting light along a photonic crystal fibre, the fibre being a fibre as defined above.

By way of example, an embodiment of the invention will now be described, with reference to the accompanying drawings, of which:

Fig. 1 is a schematic cross-section of an optical fibre;

Fig. 2 shows part of a preform suitable for making the optical fibre of Fig. 1;

Fig. 3 is a scanning electron microscope photograph of an actual fibre of the kind illustrated schematically in Fig. 1;

Fig. 4 shows an emission spectrum recorded from a fibre such as that shown in Fig. 3;

Fig. 5 shows another emission spectrum recorded from a fibre such as that shown in Fig. 3, the spectrum in this instance being recorded only for the red spectral region.

Light can be guided in an "air-mode" in a hole in a fibre waveguide such as that shown in Fig. 1. The fibre comprises a cladding formed by a triangular array of

fused, elongate tubes 1, which have been drawn from silica capillaries and contain longitudinal air holes 2. The capillaries are of circular cross-section resulting in interstitial holes 3 between the tubes 1. The fibre also comprises a core in the form of a large air hole 4 at its centre. The air hole 4 is formed in this example, as described below, by omitting a bundle of seven capillaries from part of the fibre's preform and is therefore the size of seven unit cells of the cladding material; the hole 4 is therefore much larger than the holes 2 in the fused tubes 1 and also very much larger than the interstitial holes 3.

The pitch, lattice, and filling fraction of the cladding region are chosen so as to exhibit a 2-dimensional photonic band gap (see, for example, T.A. Birks, P.J. Roberts, P. St. J. Russell, D.M. Atkin and T.J Shepherd, "Full 2-d photonic bandgaps in silica/air structures", Electron. Lett. 31 1941 (1995)). Light within the hole 4 is trapped by the photonic band gap of the surrounding material. Consequently, the light cannot propagate away from the fibre core but is constrained to travel along the fibre axis, substantially confined to the core, as a guided mode.

In the fabrication process previously disclosed for photonic crystal fibres, several hundreds of canes, at least some of which may be capillary tubes, are stacked together to form the required crystal structure on a macroscopic scale. Those canes typically have external diameters of the order of a millimetre. The entire stack is then held together while being fused and drawn down into fibre using an optical fibre drawing tower. That standard procedure will not result in a preform which is

stable or self-supporting if it has the required large air hole in the middle.

The preform shown in part in Fig. 2 provides a solution to that difficulty. Two truncated lengths 6 of stacked canes, are embedded within the stack of canes 5. The truncated canes 6 are present at both ends of the preform but they do not meet in the middle of the stack. Instead, they define a short cavity 7. The innermost canes 5 which would otherwise collapse into the cavity are thus supported from both ends in a stable fashion. A transverse cross-section through the full preform, and through the cavity 7, thus has a form similar in shape to the schematic in Fig. 1. The preform is drawn down into fibre (in one or more stages) in the usual manner. Once the fibre has been drawn, only that fibre from the central part of the preform is retained.

The fibre of Fig. 3 was fabricated using this technique. It can be seen that the structural integrity of hole 4 has been maintained in the drawing process. In general, the high quality of the lattice of the fibre of Fig. 3 is striking and the fibre cross-section closely resembles the schematic of Fig. 1. Some defects 9 can be seen, but their influence is not sufficiently deleterious to prevent air-mode guidance in the fibre.

In a particular example of the invention, the fibre is formed from 331 silica capillaries each of circular cross-section and having an external diameter of 0.8 mm and an internal diameter of about 0.7 mm. The capillaries were arranged as described with reference to Fig. 2 with seven capillaries in the centre of the array being omitted over a middle part of their lengths so as to define a cavity of length 15 cm. The preform was drawn into a fibre as described above; the resulting fibre had an

external diameter of 90 µm and a central hole 4 of diameter 15 µm.

The optical transmission spectra of the fibre were examined and are shown in Figs. 4 and 5 in each of which transmitted intensity is plotted against wavelength. The optical transmission spectra shown in Figs. 4 and 5, demonstrate that the fibre supports air-modes at a number of wavelengths; there are strong transmission peaks around 490 nm, 610 nm and 810 nm. There also appears to be, in Fig. 4, evidence of ultra-violet transmission at around 440 nm. It may be noted that the transmission pass-bands are narrow compared with those of conventional optical fibres.

In the example of the invention described with reference to the drawings the region of lower refractive index is air and the fibre is made by forming a stack of canes which includes truncated canes to define a cavity in the stack. It is within the scope of the invention for the cavity in the stack to be filled partly or completely with a material other than air and/or with one or more canes of lower refractive index than the canes used to form the cladding.

Where reference is made in this specification to "light" it should be understood that the term "light" refers to any electromagnetic radiation.

Claims

1. A photonic crystal fibre comprising a region of substantially uniform, lower refractive index which is substantially surrounded by cladding which includes regions of higher refractive index and which is substantially periodic, characterised in that the region of lower refractive index has a longest transverse dimension which is longer than a single, shortest, period of the cladding, whereby light can be substantially confined in the lower index region by virtue of a photonic band gap of the cladding material and can be guided along the fibre whilst it is so confined.
2. A photonic crystal fibre, as claimed in claim 1, in which the region of lower refractive index comprises a gas or a vacuum.
3. A photonic crystal fibre, as claimed in claim 1 or claim 2, in which the substantially periodic cladding material has a triangular lattice structure.
4. A photonic crystal fibre, as claimed in claim 3, in which the triangular lattice comprises air holes in a solid matrix.
5. A photonic crystal fibre, as claimed in any preceding claim, in which the regions of higher refractive index consist essentially of silica.
6. A photonic crystal fibre, as claimed in any preceding claim, in which the fraction of air in the cladding is at least 15% by volume based on the volume of the cladding.
7. A photonic crystal fibre, as claimed in claim 6, in which the region of the lower refractive index comprises air.

8. A photonic crystal fibre, as claimed in any preceding claim in which the region of lower refractive index is a low pressure region.
9. A photonic crystal fibre, as claimed in any preceding claim, in which the lower index region comprises a material having a non-linear optical response, whereby light may be generated by non-linear processes in the lower-index region.
10. An optical device, including photonic crystal fibre according to any preceding claim.
11. An optical device, as claimed in claim 10, comprising a spectral filtering device.
12. An optical device, as claimed in claim 10, comprising an optical amplifier.
13. An optical device, as claimed in claim 10, comprising a laser.
14. An optical device, as claimed in claim 10, comprising a sensor that is capable of sensing a property of the gas of which the region of lower refractive index is comprised.
15. A telecommunications system, including a photonic crystal fibre according to any of claims 1 to 9.
16. A telecommunications system, including an optical device according to any of claims 10 to 14.
17. A telecommunications network including a telecommunications system according to any of claims 15 to 16.
18. A method of making a photonic crystal fibre, comprising the following steps:
    (a) forming a stack of canes, the stack including at least one truncated cane which defines a cavity in the stack;
    (b) drawing the stack into a fibre having an

elongate cavity.

19. A method as claimed in claim 18 in which the optical fibre is a fibre according to any one of claims 1 to 8.

20. A method, as claimed in claim 18 or 19, in which the cavity has a transverse dimension greater than the corresponding transverse dimension of any of the canes.

21. A method, as claimed in claim 20, in which the cavity has a transverse dimension greater than the sum of the corresponding dimensions of any two of the canes.

22. A method, as claimed in any of claims 18 to 21, in which the stack of canes comprises canes which are capillaries.

23. A method, as claimed in claim 22, in which the capillaries form a triangular array.

24. A method, as claimed in claim 22 or claim 23, in which the capillaries are filled with a material other than air.

25. A photonic crystal fibre made by a method as claimed in any of claims 18 to 24.

26. A method of making a photonic crystal fibre substantially as described herein, with reference to the drawings.

27. A photonic crystal fibre substantially as described herein, with reference to the drawings.

28. A method of transmitting light along a photonic crystal fibre, the fibre being a fibre as claimed in any of claims 1 to 10.

FIG. 1

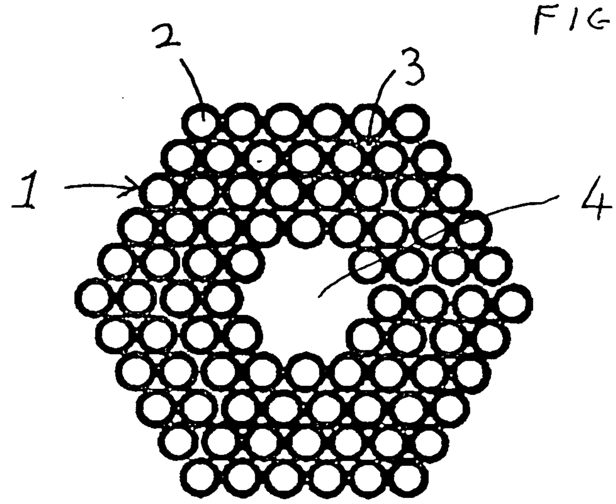

FIG. 2

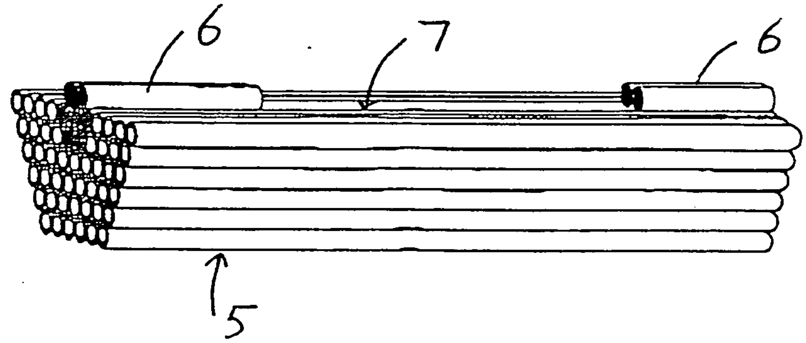

FIG. 3

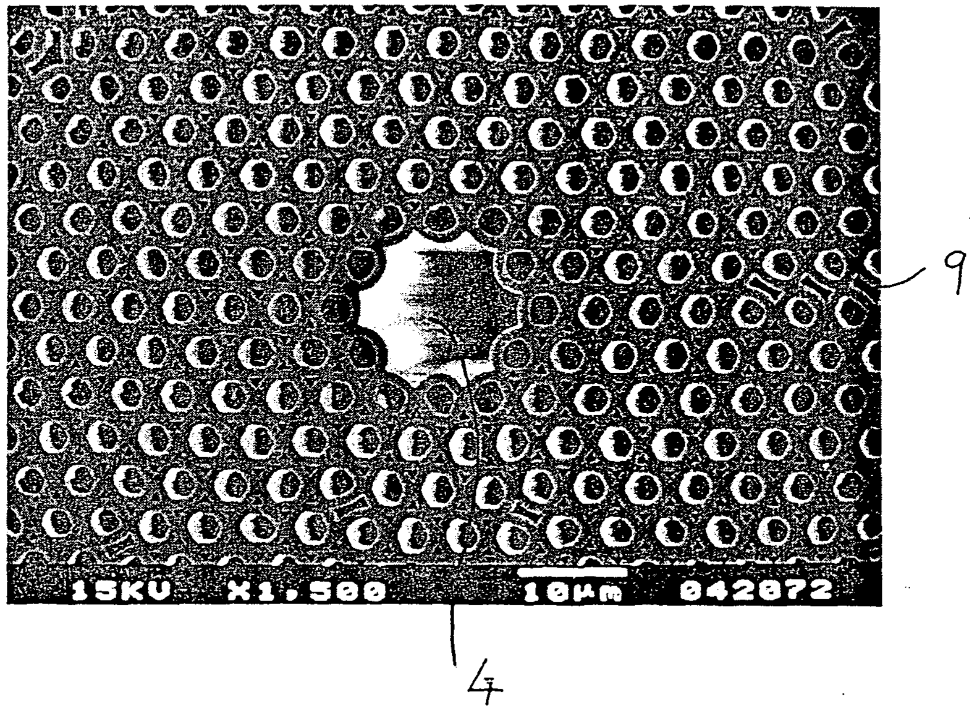

FIG. 4

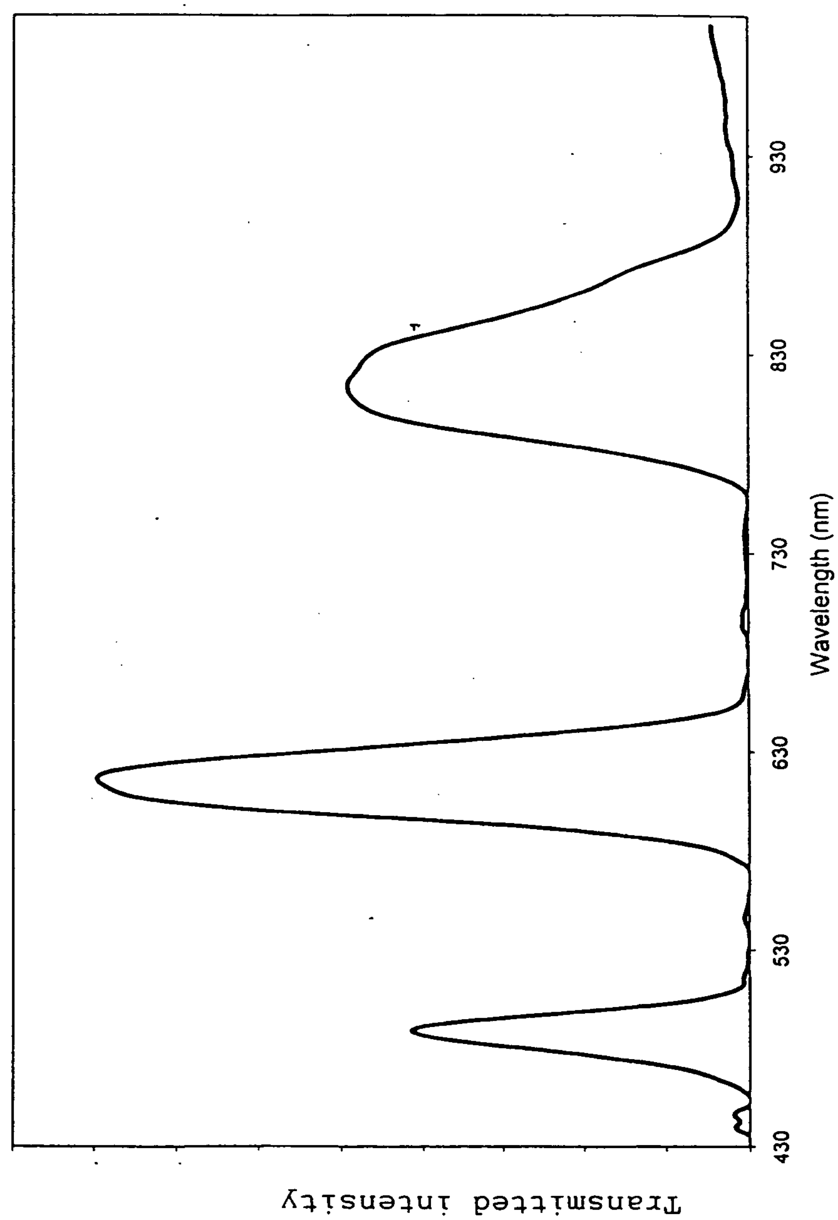
430
530
630
730
830
930
Wavelength (nm)
Transmitted intensity

FIG. 5